UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Faculty of Electronics and Computer Engineering

DESIGN AND DEVELOPMENT OF THERMOELECTRIC POWERED WIRELESS SENSOR NETWORK USING SOFT START APPROACH

Chen Wei Ping

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CHEN WEI PING

A thesis submitted
in fulfillment of the requirements for the degree of
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DECLARATION

I declare that this thesis entitled "Design and Development of Thermoelectric Powered Wireless Sensor Network using Soft Start Approach" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature: ....

Name : CHEN WEI PING

Date : 5/1/2022

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of the Master of Science in Electronic Engineering.

Signature : ....

Supervisor Name : Assoc. Prof. Dr. Kok Swee Leong

Date : 5/1/2022

DEDICATION

To my beloved family, supervisors, co-supervisors, lecturers, lab assistants as well as my best friends, Ali Mohammad Abdal-Kadhim, Ng Xue Yan, and Ng Lin Feng. Thank you for giving me mentally and moral support during the master program.

ABSTRACT

Wireless Sensor Networks (WSNs) mainly comprise of a large number of spatially distributed low-power autonomous nodes (SNs) equipped with sensors to cooperatively monitor the environmental conditions. The limited battery lifespan that is being used to operate a sensor node is the major bottleneck that restricts the extension of WSN application. The motivation of this research project is using Thermoelectric Generator (TEG) to harvest the heat energy and convert the heat energy into electrical energy for powering a sensor node. However, the energy harvested by the TEG is too small and insufficient to power up the sensor node as it is relatively power hungry. In addition, there is a power mismatch between the supply energy produced by the TEG and the energy needed by the node to carry out the required tasks. Therefore, the objective of this research project is to develop a low power management system in enabling TEG powered wireless sensor nodes to be operated smoothly. In the experiment, a TEG was sandwiched between a heating element and a heat sink in order to produce a temperature gradient between the TEG with a range between 5°C and 30°C. Then, two power management systems using two different integrated circuits of LTC3108 and MAX757 respectively were compared. Moreover, two soft start circuits based on TC54 and LM741 respectively were designed and compared in terms of sensitivity and charging time, discharging time during the operation a sensor node. These two circuits were implemented in between the capacitor storage and the sensor node. The result proved that the output voltage of TEG is boosted up using LTC3108 and MAX757 to 3.326V and 3.382V respectively and the maximum power output of TEG is around 29.48mW. Besides, it is also shown that the capacitor voltage (V_{CS}) for the proposed soft start circuit can be increased up to 3.3V with a charging time around 20s. It is also act to isolate the capacitor storage with sensor node during the charging process and activation of the sensor node. The charging time for the capacitor storage is 0.2s and the discharging time is about 4s. During the discharging time, the node is in sleep mode. This allows the power management circuit to accumulate enough of power for the next active period. The sensor node based on CC2650 consumed 22.28mW during the data transmission, while consumed 0.11mW during the sleep mode. Thus, it shows that the automatic power management for a sensor node is achievable with soft-start system which overcomes the start-up problem every time a storage capacitor has been completely discharged.

REKA BENTUK DAN PEMBANGUNAN RANGKAIAN SENSOR WAYARLES BERKUASA TERMOELEKTRIK MENGGUNAKAN PENDEKATAN PERMULAAN LEMBUT

ABSTRAK

Rangkaian Sensor Wayarles (WSN) utamanya terdiri daripada nod penderia (SNs) autonomi berkuasa rendah dalam bilangan besar yang teragih secara meluas dan dilengkapi dengan penderia untuk memantau keadaan persekitaran secara kooperatif. Bateri yang mempunyai hayat terhad digunakan untuk mengendalikan nod penderia ini merupakan penghalang utama yang mengekang pengembangan penggunaan WSN. Motivasi projek penyelidikan ini adalah menggunakan Penjana Termoelektrik (TEG) untuk mengumpul tenaga haba dan menukarkannya dalam bentuk tenaga elektrik untuk menguasakan node penderia. Walau bagaimanapun, tenaga yang diperolehi daripada TEG adalah terlalu rendah dan tidak mencukupi untuk mengoperasikan nod penderia kerana ianya memerlukan kuasa yang lebih tinggi. Tambahan pula, terdapat ketakserasian antara sumber tenaga yang diperolehi daripada TEG dan keperluan tenaga untuk nod menjalankan tugas yang diperlukan. Dengan demikian, objektif projek kajian ini adalah untuk membangunkan satu sistem pengurusan kuasa rendah yang membolehkan kuasa yang dijana oleh TEG untuk mengoperasikan nod penderia tanpa wayar dengan lancar. Dalam eksperimen kajian ini, satu TEG disusun di antara elemen pemanasan dan penyerap haba bertujuan untuk menjana kecerunan suhu dengan julat antara 5°C dan 30°C. Seterusnya, prestasi dua sistem pengurusan kuasa yang menggunakan litar bersepadu LTC3108 dan MAX757 masing-masing dibandingkan. Selanjutnya, dua litar yang menggunakan pendekatan permulaan lembut berdasarkan TC54 dan LM741 masing-masing direkabentuk dan dibandingkan kepekaan mereka, serta masa pengecasan dan penyahcasan semasa operasi suatu node penderia. Kedua-dua litar ini dipasang di antara penyimpan kapasitor dan nod penderia. Keputusan membuktikan bahawa dengan menggunakan permulaan lembut, voltan keluaran TEG tersebut dengan LTC3108 dan MAX757, dapat dipertingkatkan kepada 3.326V dan 3.382V masing-masing dan kuasa keluaran TEG tersebut adalah di antara 29.48mW. Selain daripada itu, ia juga menunjukkan bahawa voltan kapasitor (V_{CS}) yang diperolehi dengan menggunakan permulaan lembut ini boleh mencapai 3.3V dengan masa pengecasan di antara 20 saat. Ia juga berfungsi untuk mengasingkan penyimpan kapasitor daripada nod penderia semasa proses pengecasan dan pengaktifan nod penderia. Masa pengecasan penyimpan kapasitor ialah 0.2s dan penyahcasan ialah 4s. Semasa penyahcasan, nod tersebut adalah dalam mod tidur. Ini membolehkan litar pengurusan kuasa untuk mengumpul kuasa yang cukup untuk kitar aktif seterusnya. Nod penderia berdasarkan kepada CC2650 menggunakan 22.28mW semasa penghantaran data, manakala menggunakan 0.11mW semasa mod tidur. Dengan demikian, ia menunjukkan pengurusan kuasa atomatik untuk nod penderia dapat dicapai dengan menggunakan sistem pendekatan permulaan lembut yang dapat mengatasi masalah permulaan pengoperasian setiap kali penyimpan kapasitor menyahcas dengan keseluruhan.

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LIST OF ABBREVIATIONS

ADC	–	Analog to Digital Converter
BATS	–	Behavior of Bats
BJT	–	Bipolar Junction Transistor
BLE	–	Bluetooth Low Energy
CMOS	–	Complementary Metal Oxide Semiconductor
CO_2	–	Carbon Dioxide
CPU	–	Central Processing Unit
DC	–	Direct Current
EAI	–	Energy-aware Interface
EEDLS	–	Energy-Efficient Distributed Leader Selection Algorithm
EH	–	Energy Harvester
Emf	–	Electromotive Force
FB	–	Feedback
FPGA	–	Field-Programmable Gate Array
GND	–	Ground
GPIO	–	General-purpose Input/Output
GSM	–	Global System for Mobile
IC	–	Integrated Circuit
I/O	–	Input/ Output
IoMT	–	Internet of Medical Things
IP	–	Internet Protocol
IoT	–	Internet of Things
LED	–	Light-emitting Diode
LCD	–	Liquid-crystal Display
MCU	–	Microcontroller
MEMS	–	Micro-Electro-Mechanical

MOSFET	–	Metal Oxide Semiconductor Field-effect Transistor
MOX	–	Mixed Oxide
MPPT	–	Maximum Power Power Tracking
N- type	–	N-type semiconductor is a type of material used in electronics and made by adding an impurity to a pure semiconductor such as silicon or germanium. The impurities such as phosphorus, arsenic, antimony and bismuth are called donor impurities.
PIR	–	Passive InfraRed sensor
PRO	–	Professional
P-type	–	When the trivalent impurity is added to an intrinsic or pure semiconductor (silicon or germanium), then it is said to be an p-type semiconductor. Trivalent impurities such as Boron (B), Gallium (Ga), and Aluminium (Al) are called acceptor impurity.
PZT	–	Piezoelectric element
PCB	–	Printed Circuit Board
RF	–	Radio Frequency
RFID	–	Radio-frequency Identification
SoC	–	System on Chip
TCP	–	Transport Layer Protocol
TE	–	Thermal Electric
TEC	–	Thermoelectric Cooler
TEG	–	Thermoelectric Generator
TEH	–	Thermal Energy Harvesting
TI	–	Texas Instruments
Tx/Rx	–	Transmitter/ Receiver
UV	–	Ultraviolet
Wi-Fi	–	Wireless Fidelity
WSN	–	Wireless Sensor Network
WSNodes	–	Wireless Sensor Nodes

LIST OF SYMBOLS

C	–	Capacitance
D	–	Diode
I	–	Current
I_{IN}	–	Input Current
I_{LOAD}	–	Current produced by Load
I_{OUT}	–	Output Current
I_{TEG}	–	Current produced by TEG
K	–	Thomson's coefficient
L	–	Inductor
P	–	Power
P_{Losses}	–	Power loss
P_{MAX}	–	Maximum Power
P_{OUT}	–	Output Power
Q_{IN}	–	Measured Input Heat to the device
R	–	Resistance
R_L	–	Load Resistance
$V_C(t)$	–	Voltage Across the Storage Capacitor
$Vcap$	–	Capacitor Voltage
V_{CCT}	–	Voltage Produce by The Boost Converter Circuit
V_{CS}	–	The Voltage of Capacitor Storage
V_{DET-}	–	Threshold Voltage
V_{IN}	–	Input Voltage
V_{OC}	–	Open Circuit Voltage
V_{OUT}	–	Output Voltage
V_{REF}	–	Reference Voltage
V_S	–	Seebeck Voltage
$V_{Start\text{-}up}$	–	Start-up Voltage
V_{TH}	–	Threshold Voltage

V_{TL}	–	Lower Threshold Voltage
V+	–	Terminal of op-amp that receives positive voltage
V-	–	Terminal of op-amp that receives positive voltage
ΔT	–	Temperature Difference
ΔE	–	The Amount of Energy
α	–	Seebeck coefficient
ε	–	Electromotive Force
Π	–	Peltier's coefficient

LIST OF PUBLICATIONS

Journals

[1] Chen, W.P., and Kok, S.L., 2019. Design of Power Conditioning Circuit for Thermal Energy Harvester in Powering A Wireless Sensor Node. *International Journal of Recent Technology and Engineering (IJRTE)*, 8(2S6), pp. 792-796.

Conference

[1] Chen, W.P., Kok, S.L., and Ali, M.A.K., 2019. Comparison Study Between RSL10 and CC2650 Based Wireless Sensor Node for Low Power Application. *Proceedings of The 1st International Conference on Smart Community & Industry (ICSCI)*, Melaka, Malaysia, 16-18 October 2019.

[2] Ali, M.A.K., Kok, S.L., and Chen, W.P., 2019. Piezoelectric and thermoelectric hybrid energy harvester scheme evaluation for wireless sensor node. *Proceedings of The 1st International Conference on Smart Community & Industry (ICSCI)*, Melaka, Malaysia, 16-18 October 2019.

CHAPTER 1

INTRODUCTION

1.1 Background

Sensors nowadays are everywhere around us, whereby they can be found in vehicles, factories and even under the ground monitoring the soil conditions in vineyards. While it seems that sensors have been around for a while, research on wireless sensor networks (WSNs) started back in the 1980s, and it is only since 2001 that WSNs generated an increased interest from industrial and research perspectives (Shu et al., 2014). Meanwhile, Internet of Things (IoT) developed in parallel to WSN. Analysts expected that "26-75 billion installed units until 2020" will exist (Kapteina, 2019). Figure 1.1 shows the devices that are incorporated for over 20 years.

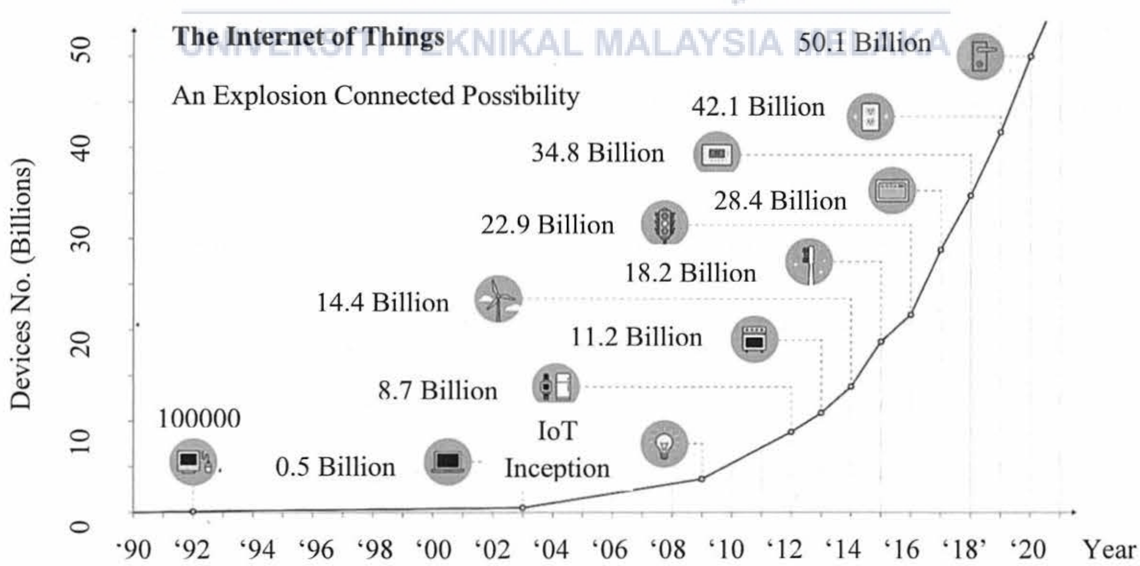

Figure 1.1: The growth of Internet of Things (IoT) (Kapteina, 2019)

WSN consists of a large number of autonomous devices called wireless sensor nodes which made up of microcontroller unit (MCU), radio transceiver unit, sensor for detecting light, heat, humidity, and temperature as well as a power supply on small boards. These sensor nodes are commonly randomly installed in some remote areas or hazardous environments like jungles, high-ways, volcanoes, and the nuclear area where people are unable and difficult to access. Since these commercial sensor nodes are mobile and power hungry, they are usually constrained by their power capability.

Traditionally, batteries are the dominant energy source for the WSN nodes to supply the electrical energy power for WSN operation but certainly not the optimal choice due to their limited lifetime. Periodic battery replacement is impractical since people unable to access the places especially for dangerous environment. Thus, the wireless sensor node is expected to be out of service and cannot accomplish its role in case of battery depletion. Battery has limited lifespan which can last only 5 years for the application of WSN using embedded microprocessor (Rashmi et al., 2017). As a matter of fact, Nechibvute, Chawanda and Luhanga (2012) denoted that the disadvantages of the battery are one of the main reasons that is restrained the manifestation and the lifespan of the mobility WSNs. In order to overcome the challenge of the restricted lifespan of the battery, the energy harvesting approach is implemented to power up the WSN.

Energy is existing in our surrounding ambient as it transfers from one system to another Lehrman (1973). Energy harvesting is one of the techniques of capturing the ambient energy and converting it into a limited magnitude of useful electrical energy that can be to power portable low-power autonomous devices. These ambient energies can be effectively harvested from various of sources. For example, light energy which can be captured by photovoltaic cells; mechanical energy which can capture by piezoelectric elements (PZT) while thermal energy can capture by Peltier elements such as thermoelectric generator (TEG).

Among these power-generating methods, driving a thermoelectric generator (TEG) from wasted heat is advantageous in that it can use a variety of heat sources for example automobile, power plants, industry and human without time constants unlike sunlight. For environmental monitoring, waste heat is easily available especially near to machinery where heat is more abundant compared to other energy source. Therefore, TEG is very efficient in environment as the heat is harvested from ambient heat source and converted into electricity.

In addition, the thermoelectric energy has attracted a great deal of attention because of its DC power, sustainability of the power source and controllable output voltage. For example, a piezoelectric or electromagnetic, AC type energy conversion device requires a rectifier to convert AC to DC, as a result the energy efficiency is reduced by the losses in the rectifier. It is also maintenance-free due to the use of highly reliable and compact solid-state device. Thus, the favourable characteristics of the thermoelectric devices promotes the development of standalone TEGs for energy harvesting in a wide range of applications as shown in Figure 1.2.

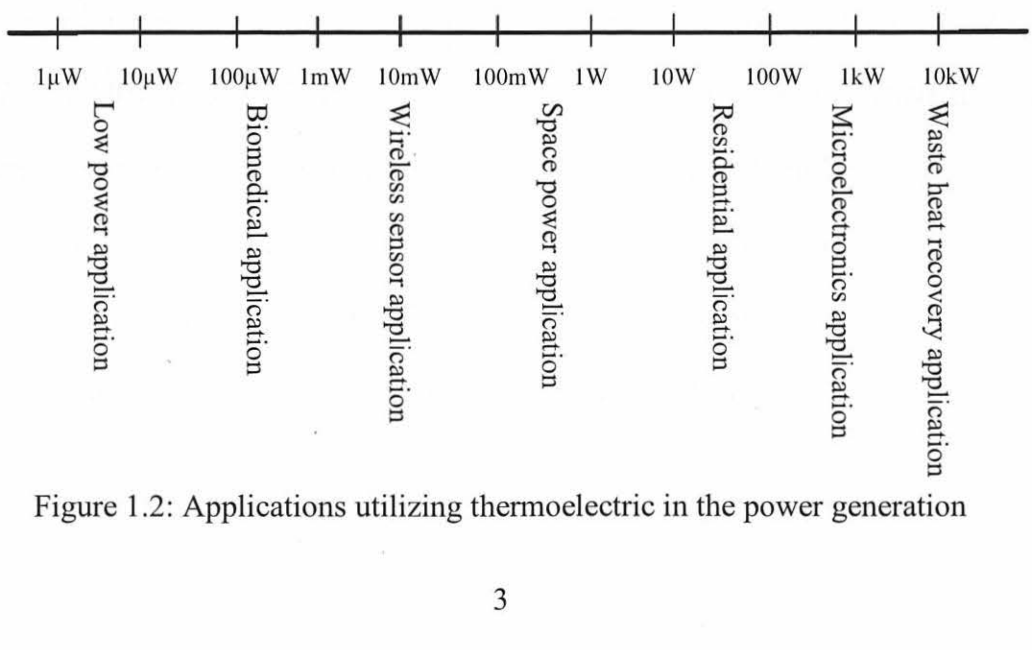

Figure 1.2: Applications utilizing thermoelectric in the power generation